Reports of the Department of Geodetic Science
Report No. 187

GEODETIC SATELLITE OBSERVATIONS IN NORTH AMERICA (SOLUTION NA-9)

by
Ivan I. Mueller, James P. Reilly, and Tomas Soler

Prepared for
National Aeronautics and Space Administration
Washington, D.C.

Contract No. NGR 36-008-093
OSURF Project No. 2514

The Ohio State University
Research Foundation
Columbus, Ohio 43212

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PREFACE

This project is under the supervision of Ivan I. Mueller, Professor of the Department of Geodetic Science at The Ohio State University, and is under the technical direction of James P. Murphy, Special Programs, Code ES, NASA Headquarters, Washington, D. C. The contract is administered by the Office of University Affairs, NASA, Washington, D. C., 20546.

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1. INTRODUCTION

The coordinates of several tracking stations tied to the NAD datum were computed at OSU through available observations to the GEOS-I satellite. Up to date results of the NA6 adjustment [Mueller et al., 1969] and NA8 adjustment [Mueller and Reilly, 1971] had been presented. The latter solution was performed using height constraints deduced from the SAO-69 geoid [Gaposchkin and Lambeck, 1970].

Recently a new detailed geoidal map with claimed accuracies of ± 2 m (on land), based on gravimetric and satellite data, was presented [Vincent, Strange and Marsh, 1971]. With the new geoid and the orthometric heights given in [NASA, 1971] more reliable height constraints were calculated and applied.

The basic purpose of this experiment was to compute the new solution NA9 by defining the origin of the system, from the point of view of error propagation, in the most favorable position applying "inner constraints" [Blaha, 1971], and imposing new weighted height constraints to all of the stations. The major differences with respect to formerly published adjustments can be seen in Table 1.

2. THEORETICAL BACKGROUND

2.1 Normal Equations for Optical Observations

The set of optical observations from MOTS and PC-1000 data had been previously screened [Mueller et al., 1969] and a set of reduced normal equations of the form

$$\dot{N}\dot{X} + \dot{U} = 0$$

obtained. The same symmetric coefficient matrix was used. This is composed of 3x3 blocks of the form [Mueller, 1968]

$$\underset{3\times 3}{\dot{N}_{kk}} = \sum_{j} M_{kj}^{-1} - \sum_{j} M_{kj}^{-1} \left(\sum_{i} M_{ij}^{-1}\right)^{-1} M_{kj}^{-1} + P_k$$

$$\underset{3\times 3}{\dot{N}_{kl}} = -\sum_{i} M_{kj} \left(\sum_{i} M_{ij}^{-1}\right)^{-1} M_{ij}$$

where

$$M_{ij} = B_{ij} P_{ij}^{-1} B_{ij}^{T}$$

$$B_{ij} = S R_3(-\alpha) R_2(-90^\circ + \delta) \begin{bmatrix} 1 & 0 & 0 \\ 0 & -\cos\delta & 0 \\ 0 & 0 & -1 \end{bmatrix}$$

$$S = \text{Solar motion matrix} = R_2(-x_p) R_1(-y_p) R_3 \text{ (Sidereal Time)}$$

and

- k, l denotes particular ground stations
- j denotes particular simultaneous event
- i denotes any ground station participating in an event
- $\sum_{i}$ is the summation over all ground stations involved in event j
- $\sum_{j}$ is the summation over all events observed by ground station k and/or l
- $\underset{3\times 3}{P_k}$ weight matrix associated with any particular ground station
- $\underset{3\times 3}{P_{ij}}$ weight matrix of any observed direction

Table 1

General Information on the Geometric Adjustment

No. of PC-1000 stations	15
No. of MOTS stations	15
No. of SECOR stations	4
Total number of ground stations	34

σ optical : $\sigma_\delta = \sigma_{\alpha \cos\delta} = 2''.0$ — Rejection criteria optical : $6''.3$

σ range : $\sigma_r = 3.5$ m — Rejection criteria range : none

$\sigma_\circ$ (a priori) $= 1.0$

Relative Position Constraints

		ΔX	ΔY	ΔZ	
3334 / 5333	Greenville, Mass.	-18.31 m	2.39 m	8.95 m	$\sigma_{\Delta X} = \sigma_{\Delta Y} = \sigma_{\Delta Z} = 0.03$ m
3648 / 5649	Hunter AFB, Ga.	-82.57 m	-39.57 m	-44.89 m	
3861 / 5861	Homestead, Fla.	1700.69 m	-564.69 m	-1761.01 m	

	NA6	NA8	NA9
Station Constraint 7073 Columbia, Mo.	$\sigma_X = \sigma_Y = \sigma_Z = 3.0$ m		none
Chord Distance Constraint 3861 Homestead, Fla. to 7043 Greenbelt, Md.	1,531.562.9 m $\sigma_d/D = 1/750,000$		1,531,560.39 m $\sigma_d/D = 1/750,000$
Height Constraint	none	Orthometric heights from [NASA,1971]; Undulations from SAO69 geoid	Same as NA8, but undulations from [Vincent et al, 1971]. See σ_h in Table 4
Inner Constraints	none	none	yes
No. of degrees of freedom	5183	5254	5228
$\Sigma V'PV$	4962.6	5082	5039
$\hat{\sigma}_\circ$ (a posteriori)	.97	.98	.98

Finally, the vector of constant terms is expressed by

$$\dot{U}_k = -\sum_j M_{kj}^{-1} \left[X_k^{\circ} - \left(\sum_i M_{ij}^{-1}\right)^{-1} \sum_i M_{ij}^{-1} X_i^{\circ} \right]$$

where as usual, the superscript ($^{\circ}$) denotes initial approximate values.

2.2 Normal Equations for Range Observations

The general form of the normal equations similarly to the optical case can be formulated as:

$$\widetilde{N}\widetilde{X} + \widetilde{U} = 0$$

where the 3x3 blocks in $\widetilde{N}$ are now computed by [Mueller, 1968]

$$\underset{3\times 3}{\widetilde{N}_{kk}} = \sum_j a_{kj}^T \widetilde{p}_{kj} a_{kj} - \sum_j a_{kj}^T \widetilde{p}_{kj} a_{kj} \left[\sum_i a_{ij}^T \widetilde{p}_{ij} a_{ij}\right]^{-1} a_{kj}^T \widetilde{p}_{kj} a_{kj}$$

$$\underset{3\times 3}{\widetilde{N}_{ki}} = -\sum_j \left[a_{kj}^T \widetilde{p}_{kj} a_{kj} \left(\sum_i a_{ij}^T \widetilde{p}_{ij} a_{ij}\right)^{-1} a_{ij}^T \widetilde{p}_{ij} a_{ij} \right]$$

and the vector of constant terms having the form

$$\widetilde{U}_k = -\sum a_{kj}^T \widetilde{p}_{kj} \widetilde{v}_{kj}$$

where

$\widetilde{v}_{kj}$ = Residual of any observed range from a particular station (resulting from a preliminary least squares adjustment of any simultaneous event with the stations held fixed)

p_{ij} = Weight of any observed range r_{ij}

$$a_{ij} = \left[\frac{X_j^{\circ} - X_i^{\circ}}{r_{ij}^{\circ}} , \frac{Y_j^{\circ} - Y_i^{\circ}}{r_{ij}^{\circ}} , \frac{Z_j^{\circ} - Z_i^{\circ}}{r_{ij}^{\circ}} \right]$$

and

$X^{\circ}, Y^{\circ}, Z^{\circ}$ = Appropriate Cartesian coordinates in the average terrestrial system.

Other subscripts and symbols have the same meaning as in the case of optical observations.

2.3 Constraint's Contributions to the Normal Equations

Two alternative definitions exist for the term "constraints". The absolute constraints represent certain conditions which have to be fulfilled exactly and with no uncertainties and the relative constraints (or weighted constraints) which have the same characteristics as the observations.

In general the contribution of the functional constraint equations

$$G(X, L_c) = 0$$

to the normal equations can be found bordering the normal equation matrix

$$\begin{bmatrix} N_{n-1} & C_n^T \\ C_n & -P_{c_n}^{-1} \end{bmatrix} \begin{bmatrix} X_n \\ -K_{c_n} \end{bmatrix} + \begin{bmatrix} U_{n-1} \\ W_n \end{bmatrix} = 0$$

from where after elimination of K_{c_n} it is easy to find

$$[N_{n-1} + C_n^T P_{c_n} C_n] X_n + U_{n-1} + C_n^T P_{c_n} W_n = 0$$

or

$$[N_{n-1} + N_n^c] X_n + U_{n-1} + U_n^c = 0 \qquad (1)$$

where N_n^c and U_n^c are the contributions to the coefficient matrix and constant vector of the normal equation due to the application of constraints. The coefficient $n-1$ represents the normal equations of the previous set (without constraints).

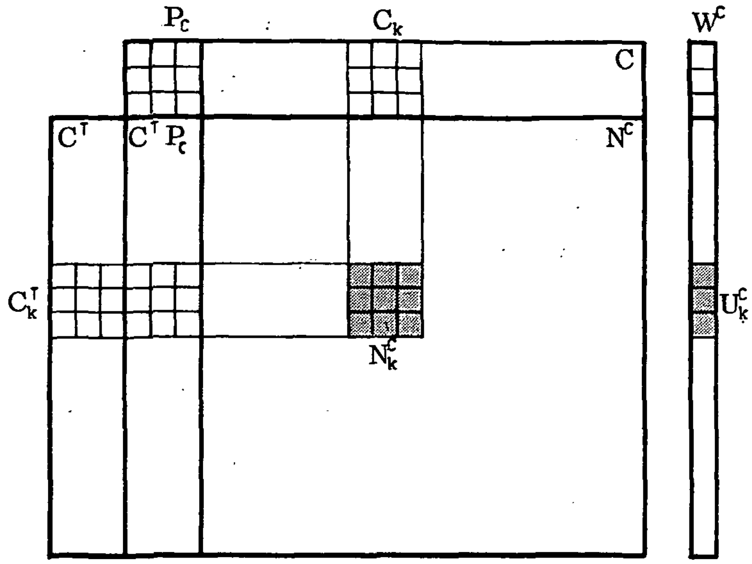
After the constraints are added the normal equations will take the usual form

$$N_n X_n + U_n = 0$$

and we are in the position to obtain the contribution from a new set of constraints.

Constraints can be applied between two stations k and l or to a single station. The contribution of these constraints to the matrix N (3x3 blocks) and U (3x1 blocks) can be schematically expressed in two different ways. Assuming that the matrix P_c is always diagonal it is possible to express:

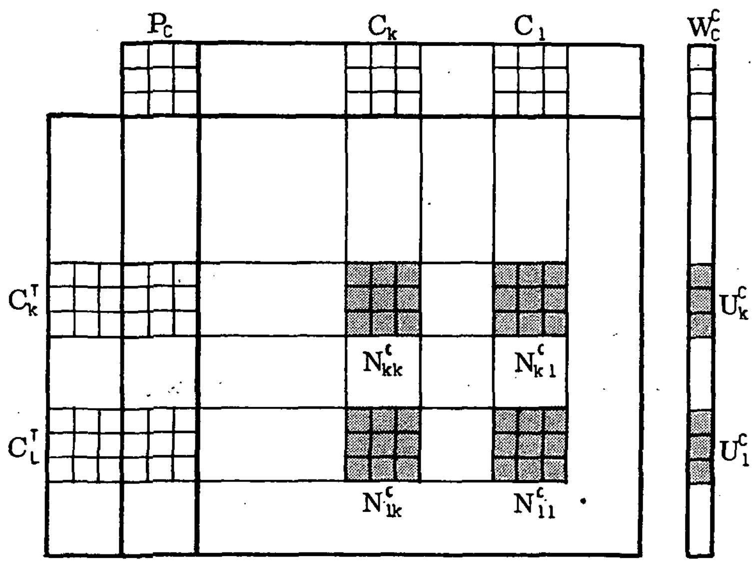
a) Contribution to the normals due to the constraint applied to station k.



$$N_k^c = C_k^T P_c C_k$$

$$U_k^c = C_k^T P_c W^c$$

b) Contribution to the normals due to the constraint between stations k and l



$$N_{kk}^c = C_k^T P_c C_k ; \quad N_{kl}^c = C_k P_c C_l$$

$$U_k^c = C_k^T P_c W^c ; \quad U_l^c = C_l^T P_c W^c \qquad \ldots . (2)$$

These blocks obtained as indicated above for the corresponding case will be the only ones computed and added to the original normal equations as expressed by formula (1).

2.31 Relative Position Constraints

Relative position constraints were used in order to combine the normal equations from the optical and range mode. The relative constraints used

and their weights are given in Table 1. The expression for the combination of normals can be written as follows.

$$[\overline{N} + N^{RC}]X + \overline{U} + U^{RC} = 0$$

or

$$\left\{\begin{bmatrix} \dot{N} & 0 \\ 0 & \tilde{N} \end{bmatrix} + N^{RC} \right\} X + \begin{bmatrix} U \\ \tilde{U} \end{bmatrix} + U^{RC} = 0$$

where N^{RC} and U^{RC} computed from (2) are the contribution to the original normal equations ($\overline{N}X + \overline{U} = 0$).

In this case the functional constraint equations are

$$X_k - X_1 = \Delta X$$

$$Y_k - Y_1 = \Delta Y$$

$$Z_k - Z_1 = \Delta Z$$

Therefore:

$$\underset{3\times3}{C_k^{RC}} = \underset{3\times3}{I} \; ; \quad \underset{3\times3}{C_1^{RC}} = \underset{3\times3}{-I}$$

and $\underset{3\times1}{U_k^{RC}} = 0$; $\underset{3\times1}{U_1^{RC}} = 0$ because $W^{RC} = G^{RC}(X_c^{\circ}, L_c^{\circ}) = 0$

where

$$P_{RC} = \begin{bmatrix} \frac{1}{\sigma^2_{\Delta X}} & 0 & 0 \\ 0 & \frac{1}{\sigma^2_{\Delta Y}} & 0 \\ 0 & 0 & \frac{1}{\sigma^2_{\Delta Z}} \end{bmatrix}$$

and

$$\underset{3\times3}{N_{kk}^{RC}} = I P_{RC} I = \underset{3\times3}{P_{RC}}$$

$$\underset{3\times3}{N_{11}} = I P_{RC} I = \underset{3\times3}{P_{RC}}$$

$$\underset{3\times3}{N_{k1}^{RC}} = \underset{3\times3}{N_{1k}^{RC}} = I P_{RC}(-I) = \underset{3\times3}{-P_{RC}}$$

Thus, the diagonal elements of P_{RC} are added to each element of the diagonal of the blocks kk and ll of the matrix of the combined normals $\bar{N}$, and subtracted from the diagonal elements of the blocks kl and lk of $\bar{N}$. There is not contribution to the vector $\bar{U}$.

2.32 Length Constraints

The range observations introduced scale into our adjustment. In addition to the SECOR scale, a distance constraint was imposed between stations 3861 and 7043, whose updated Cape Canaveral datum coordinates were derived from the high precision geodimeter traverse in the eastern United States. Due to a recent correction in their coordinates a difference of 3 m from the previously used value (see Table 1) was taken into consideration [Meade, 1972].

The functional constraint equation is

$$G^{CH}(X, L_{CH}) = 0 \qquad \text{or}$$

$$\left[(X_k - X_l)^2 + (Y_k - Y_l)^2 + (Z_k - Z_l)^2\right]^{\frac{1}{2}} = L_{kl}$$

$$\underset{3\times 1}{C_k^{CH}} = \left[\frac{X_k^o - X_l^o}{L_{kl}^o} , \frac{Y_k^o - Y_l^o}{L_{kl}^o} , \frac{Z_k^o - Z_l^o}{L_{kl}^o} \right] \qquad \text{and}$$

$$\underset{3\times 1}{C_l^{CH}} = \left[-\frac{X_k^o - X_l^o}{L_{kl}^o} , -\frac{Y_k^o - Y_l^o}{L_{kl}^o} , -\frac{Z_k^o - Z_l^o}{L_{kl}^o} \right]$$

and $$P_{CH}^{-1} = \frac{\sigma_{kl}^2}{\sigma_o^2} \qquad \begin{aligned} \sigma_{kl}^2 &= \text{Variance of the chord} \\ \sigma_o^2 &= \text{A priori variance of unit weight} \end{aligned}$$

Then the contribution to the normals are obtained applying (2)

$$\underset{3\times 3}{N_{kk}^{CH}} = (C_k^{CH})^T \, P_{CH} \, C_k^{CH}$$

$$\underset{3\times 3}{N_{ll}^{CH}} = (C_l^{CH})^T \, P_{CH} \, C_l^{CH}$$

$$\underset{3\times 3}{N_{kl}^{CH}} = (C_k^{CH})^T \, P_{CH} \, C_l^{CH}$$

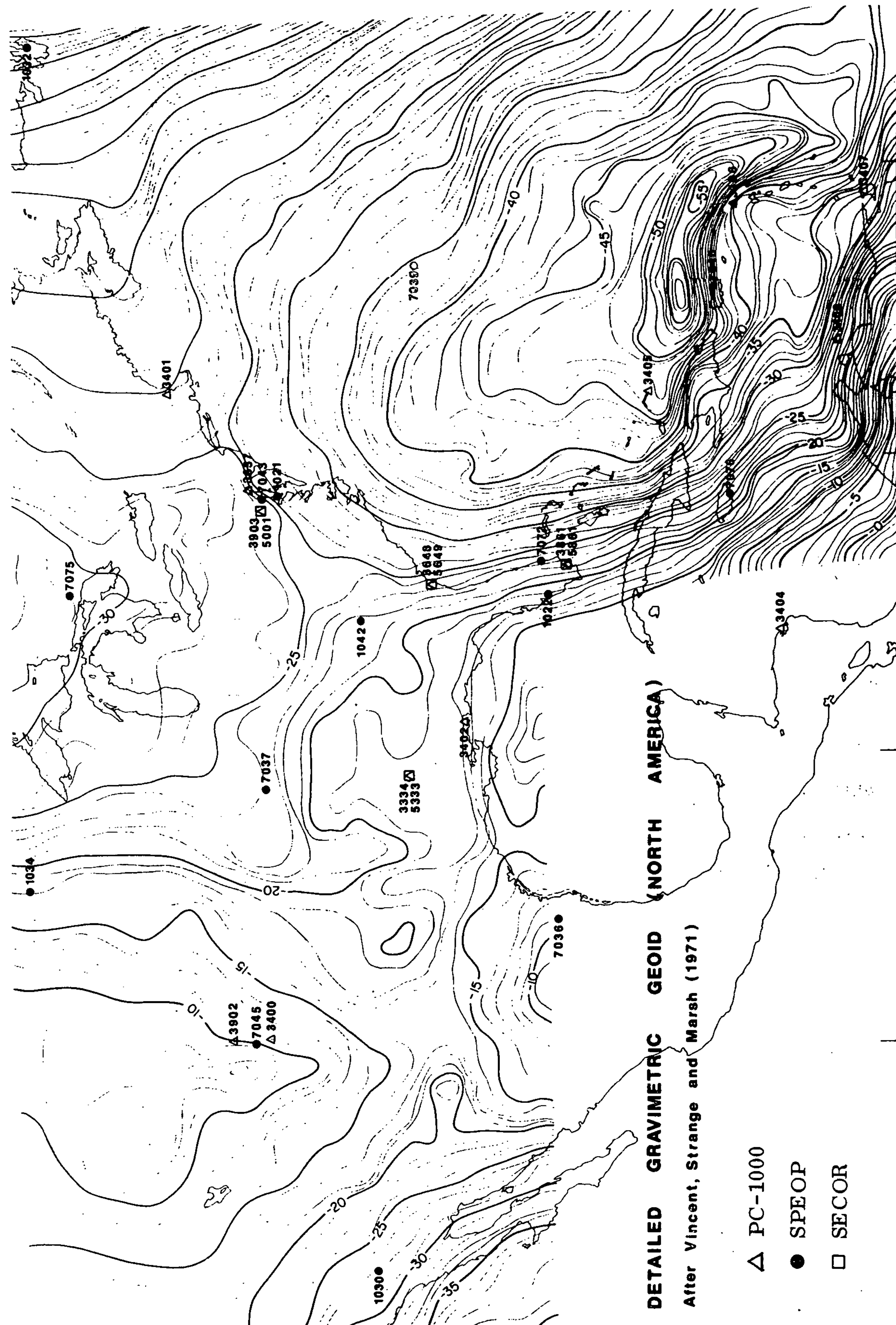

DETAILED GRAVIMETRIC GEOID (NORTH AMERICA)
After Vincent, Strange and Marsh (1971)
PC-1000
SPEOP
SECOR
45°
30°
15°
120°
105°
90°
75°
60°

Figure 1

$$\underset{3\times 1}{U_k^{CH}} = (C_k^{CH})^T P_{CH} W^{CH}$$

$$\underset{3\times 1}{U_1^{CH}} = (C_k^{CH})^T P_{CH} W^{CH}$$

The first three expressions in the above are added respectively to the blocks N_{kk}, N_{11} and N_{k1} of N; the last two expressions are added respectively to the constant vectors U_k and U_1.

2.33 Height Constraints

If the height of the station k is to be constraint, then

$$\underset{3\times 3}{N_{kk}^H} = (C_k^H)^T P_H C_k^H$$

where

$$\underset{3\times 1}{C_k^H} = [\cos\varphi_k^\circ \cos\lambda_k^\circ, \cos\varphi_k^\circ \sin\lambda_k^\circ, \sin\varphi_k^\circ]$$

and

$$P_H = \frac{1}{\sigma_{h_k}^2}$$

where φ_k° and λ_k° are the approximate geodetic coordinates and $\sigma_{h_k}^2$ is the variance of the height for station k (see Table 4).

The constant vector U^H can be computed from

$$U_k^H = (C_k^H)^T P_H W^H \qquad \text{where}$$

$$W^H = h_k - h_k^\circ$$

At all stations a weighted height constraint was imposed in order to provide a valuable strengthening to the geometric network.

After the completion of the previous adjustments (NA6, NA8), a new geoid (see Figure 1) became available [Vincent, Strange and Marsh, 1971]. With the interpolated geoidal undulations for each station and their orthometric heights given in [NASA, 1971] reliable height constraints were computed by an iterative process self-explained in Figure 2 and summarized below.

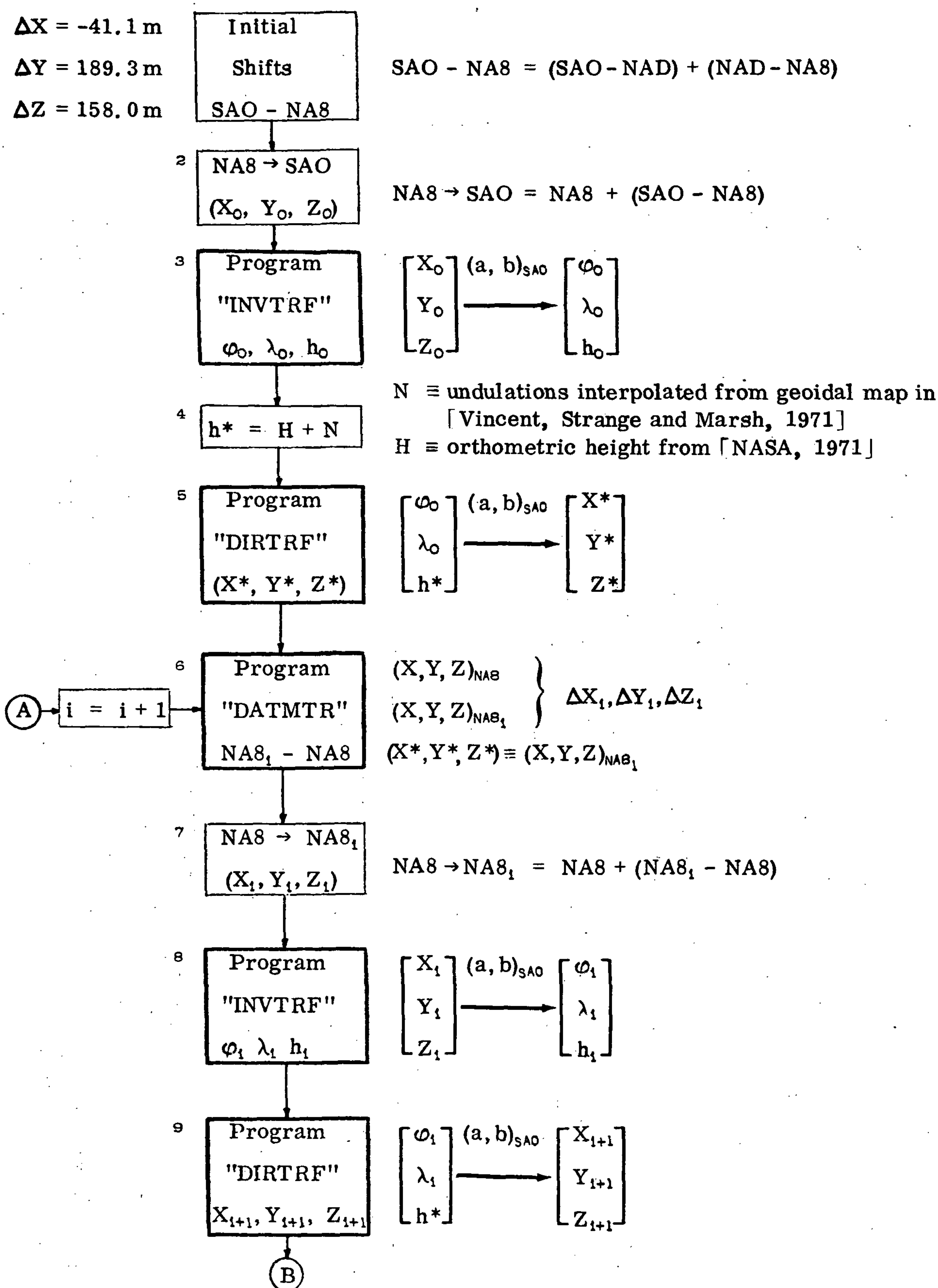

ΔX = -41.1 m
ΔY = 189.3 m
ΔZ = 158.0 m
Initial Shifts SAO - NA8
SAO - NA8 = (SAO - NAD) + (NAD - NA8)
2
NA8 → SAO (X0, Y0, Z0)
NA8 → SAO = NA8 + (SAO - NA8)
3
Program "INVTRF" φ0, λ0, h0
(a, b)SAO
4
h* = H + N
N ≡ undulations interpolated from geoidal map in [Vincent, Strange and Marsh, 1971]
H ≡ orthometric height from [NASA, 1971]
5
Program "DIRTRF" (X*, Y*, Z*)
(a, b)SAO
6
A
i = i + 1
Program "DATMTR" NA8i - NA8
(X, Y, Z)NA8
(X, Y, Z)NA8i
ΔXi, ΔYi, ΔZi
(X*, Y*, Z*) ≡ (X, Y, Z)NA8i
7
NA8 → NA8i (Xi, Yi, Zi)
NA8 → NA8i = NA8 + (NA8i - NA8)
8
Program "INVTRF" φi λi hi
(a, b)SAO
9
Program "DIRTRF" Xi+1, Yi+1, Zi+1
(a, b)SAO
B

Figure 2

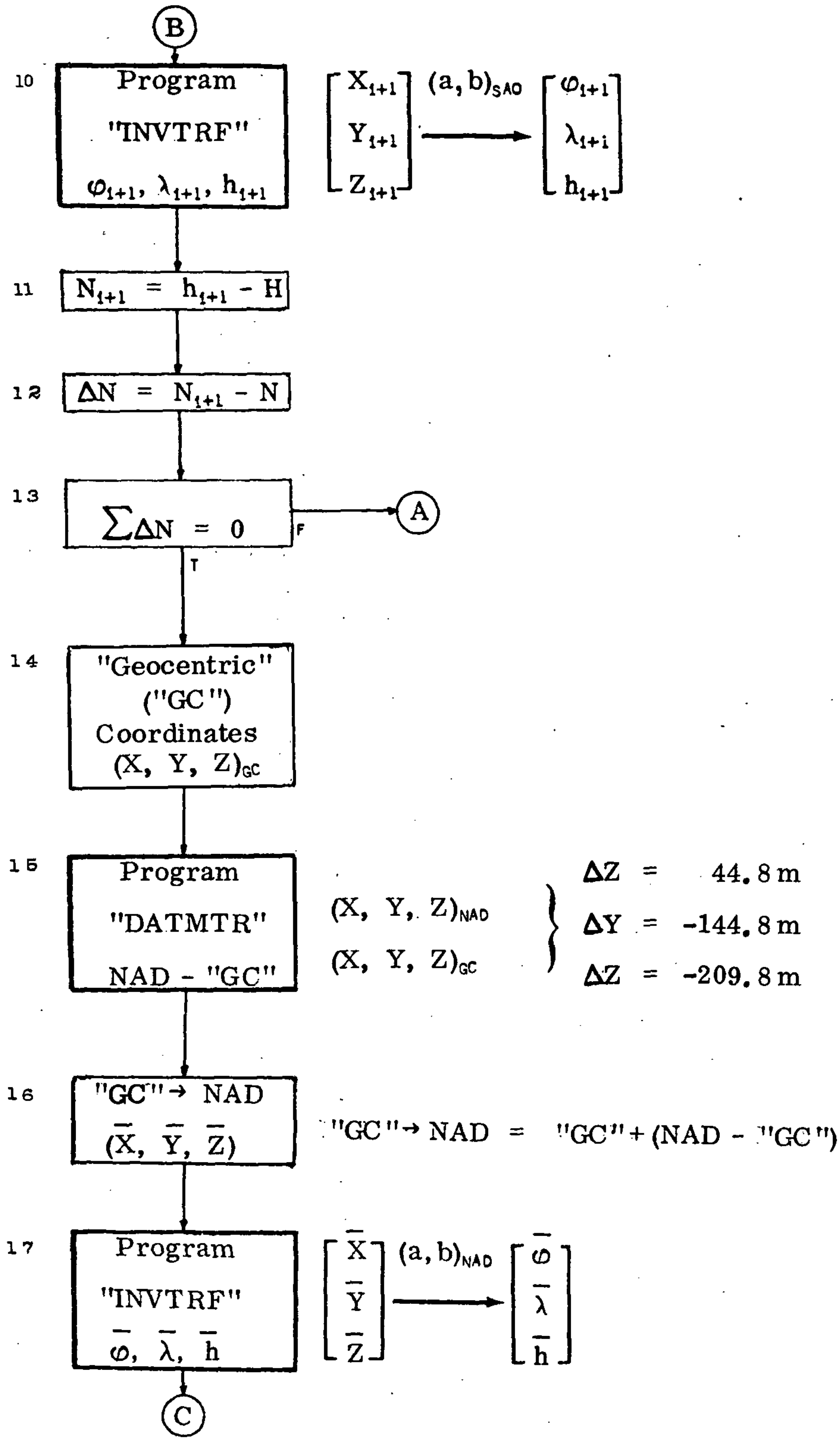


Figure 2 (continued)

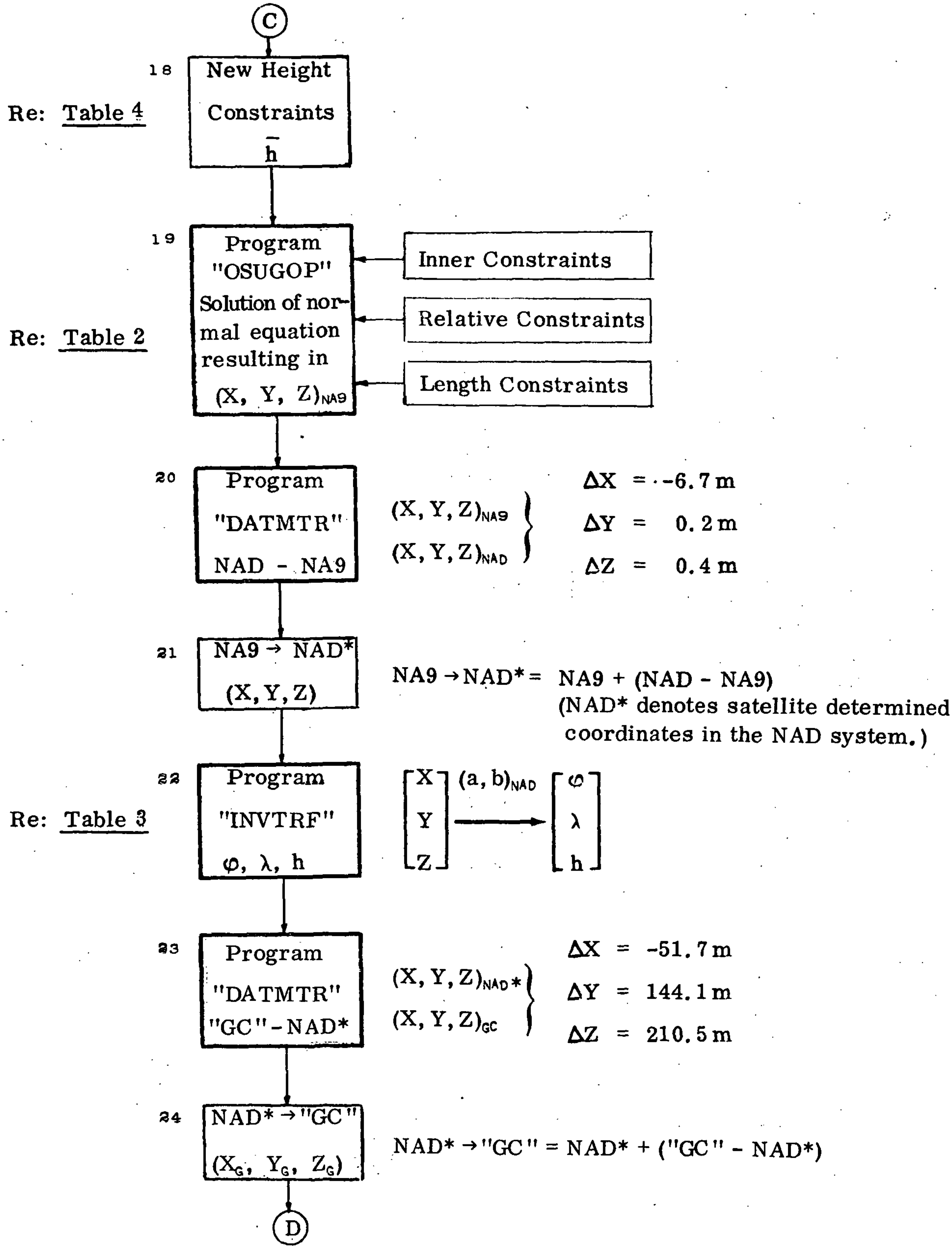


Figure 2 (continued)

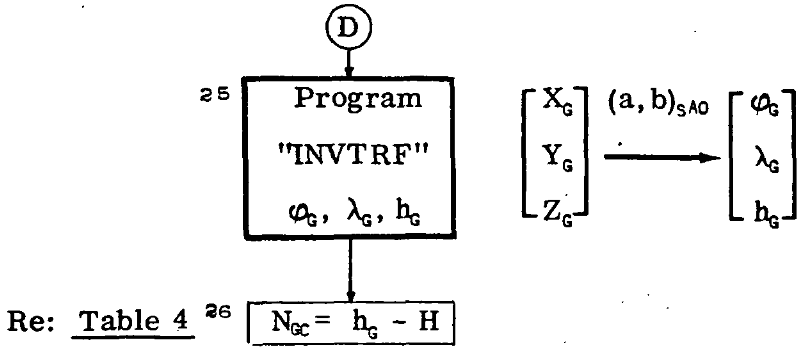


Figure 2 (continued)

From the initial values of the shifts SAO-NA8 (computed using the published shifts SAO-NAD and NAD-NA8 in [Mueller and Reilly, 1971]), the initial NA8 rectangular coordinates were shifted to the SAO-69 origin and geodetic coordinates (φ_o, λ_o, h_o) computed.

Ellipsoidal heights h^* then were calculated for each station using the undulations (N) from [Vincent, Strange and Marsh, 1971] (except for stations 1033 Fairbanks, Alaska and 3404 Swan Island whose undulations were interpolated from the SAO-69 geoid), and the sea level heights from [NASA, 1971]. With the original φ_o and λ_o, and with this new height h^* a new set of rectangular coordinates (with origin nearer to the geocenter) was obtained (X^*, Y^*, Z^*). From this set of coordinates and that of the NA8 new shift parameters (ΔX_1, ΔY_1, ΔZ_1) were computed and used to transform the NA8 set into $NA8_1$, which is nearer to the geocenter. Following this procedure iteratively, several shifts of this kind to the "geocenter" were performed until the sum of the undulation differences with respect to N approached zero. Through this process a "best" set of geocentric coordinates (GC) was obtained. Using these and the NAD coordinates of the stations, the shift parameters NAD-GC were calculated which when added to the GC coordinates resulted in Cartesian coordinates in the NAD system. From these the heights $\bar{h}$, to be constrained in the NA9 solution were computed (see step 18 in Figure 2 and Table 4).

2.34 Inner Constraints

Unlike in the NA8 adjustment, "inner constraints" (free adjustment technique) were also imposed in the NA9 solution in order to define the origin of the system in its most favorable position from the error propagation point of view [Blaha, 1971].

The functional inner constraints equations can be written as

$$C^I X = 0$$

where

$$C^I = \left[\begin{array}{ccc|ccc|c|ccc} 1 & 0 & 0 & 1 & 0 & 0 & & 1 & 0 & 0 \\ 0 & 1 & 0 & 0 & 1 & 0 & \cdots & 0 & 1 & 0 \\ 0 & 0 & 1 & 0 & 0 & 1 & & 0 & 0 & 1 \end{array}\right]$$

and C^I has as many 3x3 unit blocks as unknown points. X is the set of corrections of the approximate coordinates of the unknown points.

As it is known the "inner constraints" condition yields after the adjustment

$$\text{Trace}\ (\Sigma_x) = \text{minimum}$$

where Σ_x denotes the variance-covariance matrix of the coordinates of the ground stations following that the "inner adjustment" is the pseudo inverse solution by definition.

In the most general application when the "best" origin, orientation and scale are sought the matrix C^I has the form

$$C^I = \begin{bmatrix} C_1^I \\ C_2^I \\ C_3^I \end{bmatrix} = \left[\begin{array}{ccc|ccc|c} & \underset{3\times3}{I} & & & \underset{3\times3}{I} & & \cdots \\ \hline 0 & Z_1^o & -Y_1^o & 0 & Z_2^o & -Y_2^o & \\ -Z_1^o & 0 & X_1^o & -Z_2^o & 0 & X_2^o & \cdots \\ Y_1^o & -X_1^o & 0 & Y_2^o & -X_2^o & 0 & \\ \hline X_1^o & Y_1^o & Z_1^o & X_2^o & Y_2^o & Z_2^o & \cdots \end{array}\right]$$

where as usual $(^{\circ})$ expresses the approximate coordinates of the points.

If we represent the normal equations with the contribution of all the constraints (except inner constraints) by

$$[\overline{N} + N^{RC} + N^{CH} + N^{H}]X + \overline{U} + 0 + U^{CH} + U^{H} = 0 \qquad \text{or}$$

$$NX + U = 0$$

then the inner adjustment can be obtained by bordering the coefficient matrix N of the normal equations as

$$\begin{bmatrix} N & (C^{I})^{T} \\ C^{I} & 0 \end{bmatrix}\begin{bmatrix} X \\ -K_{I} \end{bmatrix} = \begin{bmatrix} -U \\ 0 \end{bmatrix}$$

Upon the addition of any kind of constraint to the normal equations, it becomes necessary to consider also its contribution to $\Sigma V^{T}PV$. The degrees of freedom change as well. In order to compute the proper variance of unit weight the latter must be taken into consideration.

3. THE SOLUTION

With the specific constraints mentioned above the NA9 solution was computed using the general OSUGOP program (from step 19 down in Figure 2) [Reilly et al., 1972].

The coordinates of the NA9 solution are presented in Table 2 with their corresponding standard deviations. The coordinates transformed to the NAD are shown in Table 3.

Table 4 presents the constrained heights ($\bar{h}$) used at each station, the final undulations (N_{GC}) and their differences (ΔN), compared with those published in [Vincent, Strange and Marsh, 1971]. (For the procedure see steps 23 to 26 in Figure 2). In column ΔN and in parenthesis, the differences published previously in [Vincent, Strange and Marsh, 1971] are also shown. It can be seen that only two stations show substantial disagreements (3903 Herndon, Virginia and 3407 Trinidad). It seems likely that the orthometric height as given in [NASA, 1971] for station 3903 has a gross error. The discrepancy with respect to station 3407 may be due to the fact that it is situated in the Caribbean, where large geoidal gradients being present, the interpolation is uncertain.

4. COMPARISON WITH OTHER SOLUTIONS

Table 5 summarizes the transformation parameters (systematic differences) between the NA9, the "GC", the NAD and the SAO systems (the latter from [Gaposchkin and Lambeck, 1970]). Two sets of parameters are listed. The first was obtained through the assumption that only translation exists between the sets of coordinates. The second set presents the general seven parameter solution. In this latter transformation, first the rotations were computed from direction cosines independent of the origins and scales. The scale factors were calculated from the chord distances independent of the origins and orientations. These

parameters (rotations and scale) constrained with their variances were used in the solution for all seven parameters [Kumar, 1972]. Tables 6 to 9 show the constrained solutions with the resulting variance-covariance matrices and the correlation coefficient matrices. In the variance-covariance matrices the angular units are in radians.

5. CONCLUSIONS

The solution for the station coordinates (Tables 2 and 3) appear to be completely valid. The standard deviations of the coordinates are all acceptable being more realistic than those of previous adjustments especially in the geodetic heights. The obtained origin for the "GC" system seems to be very near the geocenter, despite its geometric deviation.

Table 2

Coordinates of the North American GEOS-I Tracking Stations from the NA-9 Free Geometric Adjustment

Station	Name		NA-9	σ
1021	Blossom Point,	X	1,118,058.7	3.5
	Maryland	Y	-4,876,470.5	3.1
	MOTS 40	Z	3,942,797.5	3.1
1022	Ft. Myers,	X	807,891.3	2.6
	Florida	Y	-5,652,138.1	1.8
	SECOR	Z	2,833,333.5	1.9
1030	Mojave,	X	-2,357,204.5	6.6
	California	Y	-4,646,475.3	3.6
	MOTS 40	Z	3,668,126.2	2.9
1032	St. Johns,	X	2,602,613.4	50.2
	Newfoundland	Y	-3,419,498.3	60.3
	MOTS 40	Z	4,697,432.8	17.8
1033	College,	X	-2,299,223.8	11.7
	Alaska	Y	-1,445,844.4	33.0
	MOTS 40	Z	5,751,612.5	9.8
1034	E. Grand Fork,	X	-521,668.9	3.3
	Minnesota	Y	-4,242,203.4	4.1
	MOTS 40	Z	4,718,539.2	3.7
1042	Rosman,	X	647,535.9	2.9
	N.C.	Y	-5,178,081.5	2.4
	MOTS 40	Z	3,656,535.8	2.7
3106	Antigua Island	X	2,881,873.1	6.6
	PC-1000	Y	-5,372,311.3	3.2
		Z	1,868,379.9	5.0

Station	Name		NA-9	σ
3334	Greenville,	X	-84,952.3	4.8
	Mississippi	Y	-5,328,109.6	4.1
	PC-1000	Z	3,493,270.1	5.6
3400	Colorado Springs,	X	-1,275,160.4	9.8
	Colorado	Y	-4,798,170.6	6.0
	PC-1000	Z	3,994,031.3	5.9
3401	L.G.Hanscom Field	X	1,513,173.5	4.0
	Massachusetts	Y	-4,463,721.1	4.8
	PC-1000	Z	4,282,882.5	3.6
3402	Semmes,	X	167,298.1	3.7
	Alabama	Y	-5,482,118.2	2.4
	PC-1000	Z	3,244,869.0	3.0
3404	Swan Island	X	642,529.1	4.5
	PC-1000	Y	-6,054,080.9	4.1
		Z	1,895,525.8	4.9
3405	Grand Turk	X	1,919,526.9	5.3
	PC-1000	Y	-5,621,239.1	3.7
		Z	2,315,604.3	4.9
3406	Curacao	X	2,251,840.5	5.3
	PC-1000	Y	-5,817,062.4	3.5
		Z	1,327,044.7	6.7
3407	Trinidad	X	2,979,924.1	8.2
	PC-1000	Y	-5,513,690.3	4.6
		Z	1,180,997.4	8.9

All coordinates and standard deviations in meters.

Table 2 (continued)

Station	Name		NA-9	σ
3648	Hunter AFB,	X	832,601.2	3.4
	Georgia	Y	-5,349,695.7	2.0
	PC-1000	Z	3,360,417.5	1.9
3657	Aberdeen,	X	1,186,824.6	3.6
	Maryland	Y	-4,785,338.3	3.6
	PC-1000	Z	4,032,712.1	3.2
3861	Homestead AFB,	X	961,809.0	3.2
	Florida	Y	-5,679,305.3	1.8
	PC-1000	Z	2,729,717.7	2.1
3902	Cheyenne,	X	-1,234,651.2	9.5
	Wyoming	Y	-4,651,377.8	7.5
	PC-1000	Z	4,174,580.2	6.6
3903	Herndon,	X	1,089,019.6	10.9
	Virginia	Y	-4,843,098.5	13.8
	PC-1000	Z	3,991,566.0	9.6
5001	Herndon,	X	1,088,888.8	7.1
	Virginia	Y	-4,843,086.2	3.4
	SECOR	Z	3,991,668.3	4.4
5333	Stoneville	X	-84,970.6	4.8
	Mississippi	Y	-5,328,107.3	4.1
	SECOR	Z	3,493,279.1	5.6
5649	Hunter AFB,	X	832,518.5	3.4
	Georgia	Y	-5,349,735.3	2.0
	SECOR	Z	3,360,372.6	1.9
5861	Homestead AFB,	X	963,509.7	3.2
	Florida	Y	-5,679,870.0	1.8
	SECOR	Z	2,727,956.7	2.1

Station	Name		NA-9	σ
7036	Edinburg,	X	-828,452.8	3.8
	Texas	Y	-5,657,613.0	2.3
	MOTS 40	Z	2,816,643.5	2.8
7037	Columbia,	X	-191,252.8	2.9
	Missouri	Y	-4,967,435.7	2.6
	MOTS 40	Z	3,983,080.9	2.8
7039	Bermuda	X	2,308,250.7	5.7
	Island	Y	-4,873,750.2	3.9
	MOTS 40	Z	3,394,386.6	3.7
7040	San Juan,	X	2,465,089.9	5.7
	P.R.	Y	-5,535,083.6	3.3
	MOTS 40	Z	1,985,352.6	4.2
7043	GSFC, Greenbelt,	X	1,130,747.2	3.5
	Maryland	Y	-4,831,473.8	2.7
	PTH-100	Z	3,993,963.6	2.3
7045	Denver,	X	-1,240,427.2	4.6
	Colorado	Y	-4,760,380.6	3.4
	MOTS 40	Z	4,048,803.0	3.3
7072	Jupiter,	X	976,302.8	3.1
	Florida	Y	-5,601,548.0	2.3
	MOTS 40	Z	2,880,074.7	2.5
7075	Sudbury,	X	692,653.0	4.2
	Ontario	Y	-4,347,221.5	4.7
	MOTS 40	Z	4,600,299.3	4.2
7076	Jamaica,	X	1,384,194.3	4.8
	B.W.I.	Y	-5,905,810.3	3.1
	MOTS 40	Z	1,966,381.5	5.3

General Information:

No. of ground stations	34
No. of height constraints	34
No. of chord constraints	1
No. of degrees of freedom	5228
Quadratic sum of the residuals ($V^T PV$)	5039
Standard deviation of unit weight	0.98

Table 3

NAD Coordinates of the North American GEOS-I Tracking Stations

Station	Name		NAD	σ
1021	Blossom Point,	φ	38° 25′ 49″.81	0.11
	Maryland	λ	282 54 47.80	0.15
	MOTS 40	h	6.4 m	2.3m
1022	Ft. Myers,	φ	26 32 52.07	0.06
	Florida	λ	278 8 3.91	0.09
	SECOR	h	24.5	1.7
1030	Mojave,	φ	35 19 47.92	0.10
	California	λ	243 6 2.81	0.28
	MOTS 40	h	900.8	2.4
1032	St. Johns,	φ	47 44 27.90	0.83
	Newfoundland	λ	307 16 30.26	3.65
	MOTS 40	h	99.0	4.9
1033	College,	φ	64 52 19.60	0.47
	Alaska	λ	212 9 47.92	2.43
	MOTS 40	h	148.6	9.5
1034	E. Grand Fork,	φ	48 1 21.19	0.16
	Minnesota	λ	262 59 21.71	0.17
	MOTS 40	h	255.2	2.2
1042	Rosman,	φ	35 12 7.03	0.09
	N.C.	λ	277 7 40.55	0.12
	MOTS 40	h	914.2	2.1
3106	Antigua Island	φ	17 8 52.81	0.17
	PC-1000	λ	298 12 37.29	0.23
		h	5.4	2.4

Station	Name		NAD	σ
3334	Greenville,	φ	33° 25′ 31″.40	0.21
	Mississippi	λ	269 5 11.24	0.18
	PC-1000	h	43.2	2.0
3400	Colorado Springs,	φ	39 0 22.22	0.24
	Colorado	λ	255 7 1.29	0.40
	PC-1000	h	2190.0	4.6
3401	L.G.Hanscom Field	φ	42 27 18.01	0.14
	Massachusetts	λ	288 43 34.46	0.20
	PC-1000	h	82.2	3.4
3402	Semmes,	φ	30 46 49.58	0.10
	Alabama	λ	271 44 52.33	0.14
	PC-1000	h	79.8	2.3
3404	Swan Island	φ	17 24 17.13	0.16
	PC-1000	λ	276 3 29.28	0.15
		h	56.1	4.1
3405	Grand Turk	φ	21 25 46.80	0.16
	PC-1000	λ	288 51 13.68	0.19
		h	-5.4	3.6
3406	Curacao	φ	12 5 23.36	0.22
	PC-1000	λ	291 9 42.55	0.18
		h	38.8	3.4
3407	Trinidad	φ	10 44 32.60	0.29
	PC-1000	λ	298 23 21.59	0.28
		h	268.5	3.9

Note: The above coordinates were arrived at by applying the shifts $\Delta X = -6.7$m, $\Delta Y = 0.2$m and $\Delta Z = 0.4$m to the NA-9 coordinates and then converting these values to ellipsoidal coordinates on the ellipsoid $a = 6378206.4$ m, $b = 6356583.8$ m.

Table 3 (continued)

Station	Name		NAD			σ
3648	Hunter AFB,	φ	32°	0′	5″.88	0.08
	Georgia	λ	278	50	46.26	0.13
	PC-1000	h			23.7m	1.4m
3657	Aberdeen,	φ	39	28	19.25	0.12
	Maryland	λ	283	55	44.15	0.16
	PC-1000	h			6.2	2.5
3861	Homestead AFB,	φ	25	30	25.08	0.07
	Florida	λ	279	36	43.00	0.12
	PC-1000	h			15.2	1.7
3902	Cheyenne,	φ	41	7	58.01	0.29
	Wyoming	λ	255	8	3.32	0.40
	PC-1000	h			1883.0	4.9
3903	Herndon,	φ	38	59	34.36	0.34
	Virginia	λ	282	40	21.58	0.45
	PC-1000	h			95.1	13.4
5001	Herndon,	φ	38	59	37.78	0.16
	Virginia	λ	282	40	16.40	0.29
	SECOR	h			127.7	2.7
5333	Stoneville	φ	33	25	31.68	0.21
	Mississippi	λ	269	5	10.53	0.18
	SECOR	h			46.4	2.0
5649	Hunter AFB,	φ	32	0	4.19	0.08
	Georgia	λ	278	50	42.92	0.13
	SECOR	h			22.3	1.4
5861	Homestead AFB,	φ	25	29	21.66	0.07
	Florida	λ	279	37	39.66	0.12
	SECOR	h			16.2	1.7

Station	Name		NAD			σ
7036	Edinburg,	φ	26°	22′	45″.46	0.09
	Texas	λ	261	40	9.19	0.13
	MOTS 40	h			75.2	2.3
7037	Columbia,	φ	38	53	35.84	0.10
	Missouri	λ	267	47	42.13	0.12
	MOTS 40	h			276.5	2.1
7039	Bermuda	φ	32	21	48.92	0.13
	Island	λ	295	20	33.20	0.24
	MOTS 40	h			23.1	2.6
7040	San Juan,	φ	18	15	26.46	0.14
	P.R.	λ	294	0	21.85	0.20
	MOTS 40	h			58.4	3.0
7043	GSFC, Greenbelt,	φ	39	1	15.58	0.08
	Maryland	λ	283	10	19.91	0.15
	PTH-100	h			50.9	2.4
7045	Denver,	φ	39	38	48.06	0.12
	Colorado	λ	255	23	41.80	0.20
	MOTS 40	h			1793.0	2.4
7072	Jupiter,	φ	27	1	13.29	0.08
	Florida	λ	279	53	12.39	0.12
	MOTS 40	h			26.3	2.1
7075	Sudbury,	φ	46	27	21.11	0.18
	Ontario	λ	279	3	10.33	0.21
	MOTS 40	h			278.0	2.6
7076	Jamaica,	φ	18	4	32.60	0.18
	B.W.I.	λ	283	11	26.57	0.16
	MOTS 40	h			474.8	2.7

Table 4

Height Constraints and Undulations
(all units in meters)

Number	Station	Constraints $\bar{h}$	Constraints σ_h	N N_{GC} *	N [Vincent et al., 1971]	ΔN
1021	Blossom Pt., Md.	9	3	- 27	-26	- 1 (- 7)
1022	Fort Myers, Florida	23	3	- 16	-18	2 (1)
1030	Goldstone, Calif.	898	3	- 23	-27	4 (8)
1032	St. John's, Nswf.	102	5	12	13	- 1
1033+	Fairbanks, Alaska	145	10	16		
1034	E. Grand Forks, Minn.	251	3	- 13	-18	5 (11)
1042	Rosman, N.C.	916	3	- 23	-22	- 1 (- 3)
3106	Antigua, W.I.	12	3	- 45	-40	- 5 (- 2)
3334	Stoneville, Mississippi	45	3	- 20	-19	- 1
3400	Colorado Springs, Col.	2184	5	- 4	-10	6
3401	Bedford, Mass.	89	5	- 27	-21	- 6
3402	Semmes, Alabama	84	3	- 21	-18	- 3 (-12)
3404+	Swan Island	79	7	- 32		
3405	Grand Turk, B.I.	0	5	- 51	-47	- 4 (-27)
3406	Curacao, N. Antilles	44	5	- 30	-26	- 4
3407	Trinidad, Tobago	285	5	- 50	-34	-16
3648	Hunter AFB, Georgia	19	3	- 19	-24	5 (- 5)
3657	Aberdeen, Maryland	7	3	- 27	-26	- 1 (- 4)
3861	Homestead, Florida	16	3	- 22	-22	0
3902	Cheyenne, Wyoming	1882	5	- 8	-10	2
3903	Herndon, Virginia	132	3	-100	-26	-74
5001	Herndon, Virginia	132	3	- 27	-26	- 1
5333	Stoneville, Mississippi	45	3	- 17	-19	2
5649	Hunter AFB, Georgia	23	5	- 23	-23	0
5861	Homestead, Florida	22	3	- 27	-22	- 5 (- 5)
7036	Edinburg, Texas	72	3	- 8	-11	3
7037	Columbia, Missouri	270	3	- 17	-24	7 (10)
7039	Bermuda	26	3	- 38	-36	- 2 (- 2)
7040	San Juan, P.R.	57	5	- 40	-41	1 (5)
7043	Greenbelt, Maryland	56	3	- 30	-26	- 4 (-15)
7045	Denver, Colorado	1787	3	- 7	-10	3 (16)
7072	Jupiter, Florida	26	3	- 23	-24	1 (1)
7075	Sudburg, Canada	276	3	- 28	-31	3 (20)
7076	Kingston, Jamaica	473	3	- 20	-23	3 (20)

*The "geocentric" coordinates were obtained from the NA-9 by adding the following shifts: $\Delta X = -51.7\,m$, $\Delta Y = 144.1\,m$, $\Delta Z = 210.5\,m$.

+Undulations from SAO 69 geoid.

Table 5

Transformation Parameters

		NA9-NAD	NA9-"GC"	NA9-SAO	"GC"-NAD
No Stations		28	34	11	32
3 param. transf.	ΔX(m)	6.7 ± 1.3	51.7 ± 0.7	35.3 ± 2.6	-44.8 ± 1.3
	ΔY(m)	-0.2 ± 1.1	-144.1 ± 0.8	-148.3 ± 2.6	144.8 ± 1.1
	ΔZ(m)	-0.4 ± 1.2	-210.5 ± 0.9	-175.0 ± 2.6	209.8 ± 1.2
7 parameter transf.*	ΔX(m)	-3.5 ± 2.4	40.0 ± 1.6	25.9 ± 6.6	-38.0 ± 2.2
	ΔY(m)	-18.4 ± 2.5	-142.9 ± 1.1	-200.7 ± 7.9	125.5 ± 2.3
	ΔZ(m)	19.1 ± 2.5	-204.1 ± 1.5	-172.5 ± 7.6	226.7 ± 2.3
	$\theta_Z('')$	-0.83 ± 0.06	-0.34 ± 0.04	-0.62 ± 0.19	-0.36 ± 0.06
	$\theta_Y('')$	0.53 ± 0.05	-0.20 ± 0.03	0.14 ± 0.16	0.83 ± 0.04
	$\theta_X('')$	-0.14 ± 0.08	-0.21 ± 0.05	0.94 ± 0.24	-0.10 ± 0.07
	$\epsilon(\times 10^6)$	-4.23 ± 0.32	-0.15 ± 0.05	-6.90 ± 1.20	-4.04 ± 0.29

*Rotation and scale factor parameters constrained.

Table 6

TRANSFORMATION PARAMETERS: NA9-NAD

Scale Factor and Rotation Parameters Constrained to Independently Determined Values

ΔX METERS	ΔY METERS	ΔZ METERS	ϵ (10.D+5)	θ_Z SECONDS	θ_Y SECONDS	θ_X SECONDS
-3.51	-18.36	19.09	-4.23	-0.83	0.53	-0.14

VARIANCE - COVARIANCE MATRIX

0.573D+01	0.123D+01	0.192D+01	-0.374D-07	0.526D-06	0.272D-06	-0.365D-06
0.123D+01	0.606D+01	0.724D+00	0.512D-06	0.222D-06	0.758D-07	-0.506D-06
0.192D+01	0.724D+00	0.606D+01	-0.364D-06	0.290D-06	0.924D-07	-0.735D-06
-0.374D-07	0.512D-06	-0.364D-06	0.100D-12	-0.839D-15	0.383D-17	0.103D-14
0.526D-06	0.222D-06	0.290D-06	-0.839D-15	0.922D-13	0.160D-13	-0.573D-13
0.272D-06	0.758D-07	0.924D-07	0.383D-17	0.160D-13	0.541D-13	-0.207D-13
-0.365D-06	-0.506D-06	-0.735D-06	0.103D-14	-0.573D-13	-0.207D-13	0.145D-12

COEFFICIENTS OF CORRELATION

0.100D+01	0.208D+00	0.326D+00	-0.493D-01	0.723D+00	0.489D+00	-0.400D+00
0.208D+00	0.100D+01	0.119D+00	0.657D+00	0.297D+00	0.132D+00	-0.540D+00
0.326D+00	0.119D+00	0.100D+01	-0.467D+00	0.388D+00	0.161D+00	-0.785D+00
-0.493D-01	0.657D+00	-0.467D+00	0.100D+01	-0.872D-02	0.521D-04	0.851D-02
0.723D+00	0.297D+00	0.388D+00	-0.872D-02	0.100D+01	0.227D+00	-0.495D+00
0.489D+00	0.132D+00	0.161D+00	0.521D-04	0.227D+00	0.100D+01	-0.234D+00
-0.400D+00	-0.540D+00	-0.785D+00	0.851D-02	-0.495D+00	-0.234D+00	0.100D+01

Table 7

TRANSFORMATION PARAMETERS: NA9-GC

Scale Factor and Rotation Parameters Constrained to Independently Determined Values

ΔX METERS	ΔY METERS	ΔZ METERS	ϵ (10.D+5)	θ_Z SECONDS	θ_Y SECONDS	θ_X SECONDS
40.00	-142.92	-204.13	-0.15	-0.34	-0.20	-0.21

VARIANCE - COVARIANCE MATRIX

0.268D+01	0.621D+00	0.686D+00	-0.172D-08	0.224D-06	0.142D-06	-0.147D-06
0.621D+00	0.129D+01	0.936D+00	0.138D-07	0.963D-07	0.384D-07	-0.192D-06
0.686D+00	0.936D+00	0.212D+01	-0.857D-08	0.108D-06	0.347D-07	-0.287D-06
-0.172D-08	0.138D-07	-0.857D-08	0.258D-14	-0.470D-17	0.659D-17	0.129D-17
0.224D-06	0.963D-07	0.108D-06	-0.470D-17	0.376D-13	0.830D-14	-0.216D-13
0.142D-06	0.384D-07	0.347D-07	0.659D-17	0.830D-14	0.295D-13	-0.102D-13
-0.147D-06	-0.192D-06	-0.287D-06	0.129D-17	-0.216D-13	-0.102D-13	0.560D-13

COEFFICIENTS OF CORRELATION

0.100D+01	0.335D+00	0.288D+00	-0.208D-01	0.706D+00	0.505D+00	-0.379D+00
0.335D+00	0.100D+01	0.567D+00	0.239D+00	0.438D+00	0.197D+00	-0.715D+00
0.288D+00	0.567D+00	0.100D+01	-0.116D+00	0.383D+00	0.139D+00	-0.834D+00
-0.208D-01	0.239D+00	-0.116D+00	0.100D+01	-0.477D-03	0.756D-03	0.107D-03
0.706D+00	0.438D+00	0.383D+00	-0.477D-03	0.100D+01	0.249D+00	-0.471D+00
0.505D+00	0.197D+00	0.139D+00	0.756D-03	0.249D+00	0.100D+01	-0.251D+00
-0.379D+00	-0.715D+00	-0.834D+00	0.107D-03	-0.471D+00	-0.251D+00	0.100D+01

Table 8

TRANSFORMATION PARAMETERS: NA9-SAO

Scale Factor and Rotation Parameters Constrained to Independently Determined Values

ΔX METERS	ΔY METERS	ΔZ METERS	ε (10.D+5)	θ_Z SECONDS	θ_Y SECONDS	θ_X SECONDS
25.89	-200.72	-172.54	-6.90	-0.62	0.14	0.94

VARIANCE - COVARIANCE MATRIX

0.441D+02	0.800D+01	0.129D+02	-0.644D-06	0.505D-05	0.318D-05	-0.242D-05
0.800D+01	0.622D+02	-0.231D+01	0.730D-05	0.181D-05	0.618D-06	-0.498D-05
0.129D+02	-0.231D+01	0.582D+02	-0.533D-05	0.180D-05	0.422D-06	-0.645D-05
-0.644D-06	0.730D-05	-0.533D-05	0.145D-11	0.220D-14	0.144D-14	-0.432D-14
0.505D-05	0.181D-05	0.180D-05	0.220D-14	0.876D-12	0.186D-12	-0.380D-12
0.318D-05	0.618D-06	0.422D-06	0.144D-14	0.186D-12	0.610D-12	-0.143D-12
-0.242D-05	-0.498D-05	-0.645D-05	-0.432D-14	-0.380D-12	-0.143D-12	0.131D-11

COEFFICIENTS OF CORRELATION

0.100D+01	0.153D+00	0.255D+00	-0.804D-01	0.811D+00	0.612D+00	-0.318D+00
0.153D+00	0.100D+01	-0.383D-01	0.768D+00	0.246D+00	0.100D+00	-0.552D+00
0.255D+00	-0.383D-01	0.100D+01	-0.579D+00	0.252D+00	0.708D-01	-0.739D+00
-0.804D-01	0.768D+00	-0.579D+00	0.100D+01	0.195D-02	0.153D-02	-0.313D-02
0.811D+00	0.246D+00	0.252D+00	0.195D-02	0.100D+01	0.254D+00	-0.354D+00
0.612D+00	0.100D+00	0.708D-01	0.153D-02	0.254D+00	0.100D+01	-0.160D+00
-0.318D+00	-0.552D+00	-0.739D+00	-0.313D-02	-0.354D+00	-0.160D+00	0.100D+01

Table 9

TRANSFORMATION PARAMETERS: "GC"-NAD

Scale Factor and Rotation Parameters Constrained to Independently Determined Values

ΔX METERS	ΔY METERS	ΔZ METERS	ϵ (10.D+5)	θ_Z SECONDS	θ_Y SECONDS	θ_X SECONDS
-38.03	125.48	226.72	-4.04	-0.36	0.83	-0.10

VARIANCE - COVARIANCE MATRIX

0.483D+01	0.972D+00	0.153D+01	-0.343D-07	0.430D-06	0.230D-06	-0.288D-06
0.972D+00	0.510D+01	0.486D+00	0.446D-06	0.179D-06	0.616D-07	-0.410D-06
0.153D+01	0.486D+00	0.507D+01	-0.312D-06	0.227D-06	0.718D-07	-0.593D-06
-0.343D-07	0.446D-06	-0.312D-06	0.867D-13	-0.578D-15	0.221D-16	0.681D-15
0.430D-06	0.179D-06	0.227D-06	-0.578D-15	0.750D-13	0.131D-13	-0.449D-13
0.230D-06	0.616D-07	0.716D-07	0.221D-16	0.131D-13	0.464D-13	-0.166D-13
-0.288D-06	-0.410D-06	-0.593D-06	0.681D-15	-0.449D-13	-0.166D-13	0.117D-12

COEFFICIENTS OF CORRELATION

0.100D+01	0.196D+00	0.309D+00	-0.529D-01	0.714D+00	0.485D+00	-0.384D+00
0.196D+00	0.100D+01	0.955D-01	0.671D+00	0.290D+00	0.127D+00	-0.531D+00
0.309D+00	0.955D-01	0.100D+01	-0.471D+00	0.369D+00	0.148D+00	-0.771D+00
-0.529D-01	0.671D+00	-0.471D+00	0.100D+01	-0.717D-02	0.348D-03	0.677D-02
0.714D+00	0.290D+00	0.369D+00	-0.717D-02	0.100D+01	0.221D+00	-0.480D+00
0.485D+00	0.127D+00	0.148D+00	0.348D-03	0.221D+00	0.100D+01	-0.226D+00
-0.384D+00	-0.531D+00	-0.771D+00	0.677D-02	-0.480D+00	-0.226D+00	0.100D+01

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